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CARBON STORAGE OF BOTTOMLAND HARDWOOD AFFORESTATION IN THE LOWER MISSISSIPPI VALLEY, USA

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Abstract: The emerging carbon market is an increasingly important source of finance for bottomland hardwood afforestation in the Lower Mississippi River Valley (LMV). Notwithstanding, there is a scarcity of empirical estimates of carbon sequestration specific to the region and we sought to address this outstanding need. We evaluated tree measurements from known-age bottomland hardwood stands from a chronosequence of sites in the LMV, drawing on 540 plot measurements within 67 stands. We derived a model of live tree biomass carbon as a function of stand age. The model explained 83% of the variation in live tree biomass carbon at the stand level, and provides a more accurate projection for application in the LMV than broader regional models currently available. Modeled live tree biomass carbon was greater than the corresponding regional estimate used in the U.S. Department of Energy's voluntary greenhouse gas reporting program for years 20 through 90 (up to 59% greater at year 50), but trended toward convergence at mature stages.

Key Words: biomass, afforestation, climate change mitigation, forested wetlands

INTRODUCTION

Emerging markets for carbon offsets have created new opportunities to finance afforestation in the U.S. and worldwide. In the Lower Mississippi River Valley (LMV), which extends from southern Illinois to Louisiana, carbon finance has subsidized afforestation of at least 31,300 ha of agricultural land as of 2008 (personal communication: Environmental Synergy Inc., The Conservation Fund, Utilitree, Powertree, The Nature Conservancy, Winrock International).

This region receives increasing attention from carbon market entrepreneurs, attracted in part by the scientific evidence that bottomland forests have high capacity to sequester carbon in tree biomass (Brinson 1990). Although LMV soils in the vernacular are synonymous with high productivity, there is a scarcity of published growth and yield studies with which to substantiate this for bottomland hardwood afforestation in the LMV, all the more notable given the recent history and magnitude of the practice in the region (Stanturf et al. 2001, Gardiner and Oliver 2005, King et al. 2007). Only recently has an effort been made to specifically validate the widely used Forest Vegetation Simulator (FVS) growth model for use in the LMV (Hohl et al. unpublished). Consequently, there is considerable disparity in carbon sequestration estimates for afforestation of bottomland hardwoods (unpublished sources, Birdsey 1996, Smith et al. 2006).

To address this need, the revisions to the U.S. Department of Energy 1605(b) voluntary greenhouse gas reporting guidelines assembled regional volume and carbon yield tables for a range of forest types and practices in the U.S. (Smith et al. 2006). These "look-up tables" as they are popularly known provide broad regional estimates based on FORCARB and ATLAS model projections using U.S. Forest Service Forest Inventory and Analysis (FIA) data (Mills and Zhou 2003, Smith et al. 2006). Practice has found these estimates are less reliable at finer scales, which has been our experience when applying average values for the South Central U.S. to the LMV.

Consequently, there remains a need for more accurate projections of forest carbon yields for bottomland hardwood afforestation specific to the LMV. More reliable projections would foster investor confidence and ensure continued access to carbon finance for this practice. In this paper, we project live tree biomass carbon yields for bottomland hardwood afforestation in the LMV by modeling tree measurement data from a chronosequence constructed from known-age stands assembled for the region.

MATERIALS AND METHODS

Study Area and Measurement Sites

We obtained tree measurements from planted and naturally regenerated bottomland hardwood stands of known age in the LMV in the states of Arkansas, Mississippi and Louisiana (Figure 1).

Plantations. Twenty-nine planted stands ranged from 7 to 39 years old (Table 1). This is the longest chronosequence of bottomland hardwood plantations obtainable because afforestation in this region was rare before 1990 prior to the U.S. Department of Agriculture Wetland Reserve Program being initiated (Krinard and Johnson 1988, Meadows and Goelz 1992, Twedt 2004). Estimated site indices on plantations ranged from 81 (Perry clay) to 103 (Commerce loam) ft height at age 50 for Nuttall oak (*Quercus texana* Buckley = *Quercus nuttallii* Palmer) (Broadfoot 1976). Forty-three percent of sites were on Sharkey clay, which occupies 14% of the LMV region and are more predominant than any other single soil type (Groninger et al. 1999). Topography on all sites was uniformly level.

Plantations were either hand- or machine-planted with one-year old seedlings at a range of spacings from 478 to 1,345 stems per ha. Stand age and history were determined through consultation with local land managers and by inspection of increment cores. No stands had been subject to heavy thinnings or natural disturbance. Composition of planted stems was dominated by bottomland red oaks (cherrybark oak (*Quercus pagoda* Raf.), water oak (*Quercus nigra* L.), Nuttall oak, and willow oak (*Quercus phellos* L.)), with varying representation of green ash (*Fraxinus pennsylvanica* Marsh.), swamp chestnut oak (*Quercus michauxii* Nutt.), sweet gum (*Liquidambar styraciflua* L.), cottonwood (*Populus deltoides* Bartr. ex Marsh.), and baldcypress (*Taxodium distichum* L.). There was some natural recruitment of American elm (*Ulmus Americana* L.), sugarberry (*Celtis laevigata* Willd.), persimmon (*Diospyros virginiana* L.), and black willow (*Salix nigra* Marsh.). No pure species stands or stands without natural recruitment were available for measurement.

Naturally Regenerated Stands. We obtained measurements from 30 naturally regenerated bottomland hardwood stands of known age, from four to 53 years old, in the Delta National Forest near Rolling Fork, Mississippi. Forest types included sweet gum-Nuttall oak-willow oak, sugarberry-American elm-green ash, and overcup oak-water hickory. Soil type was predominately Sharkey clay. None of the stands had been thinned or had other intermediate silvicultural treatment. Stands were even-aged stands regenerating from clearcuts. Age was based on increment cores and stand records maintained by the Delta National Forest.

In the absence of any plantations or other even-aged stands older than 53 years, measurements from eight mature uneven-aged bottomland hardwood stands of natural origin from the Delta National Forest were collected. Stands were measured and aged (at 82, 87, 96, 96, 104, 106, 120, and 121 years) based on increment cores taken from the dominant cohort, believed to represent age of initiation. Only stands with apparent initiating cohorts from examining diameter distributions were used in the analysis.

Field Measurements

We collected data from 110 plots on 24 planted bottomland hardwood stands (Table 1). These data were augmented with 55 plots from five additional planted sites that were measured previously by Twedt and Wilson (2002). Measurements of 375 plots from 38 naturally regenerated stands were obtained from Baker (1998) and this study. Stands were sampled systematically with fixed radius (8 m, 10 m, 11.4 m, or 14 m, depending on stem density) circular plots spaced at $\sim$50 m intervals along transects. Within each plot, diameter at breast height (dbh) was recorded for all live trees $\geq$ 2.5 cm dbh from stands $<$ 20 years old, or $\geq$ 10 cm dbh from stands $>$ 20 years old (where few stems remained in size classes $<$ 10 cm dbh).

Data Analysis

Above- and below-ground (coarse roots) live tree biomass was estimated from dbh applying

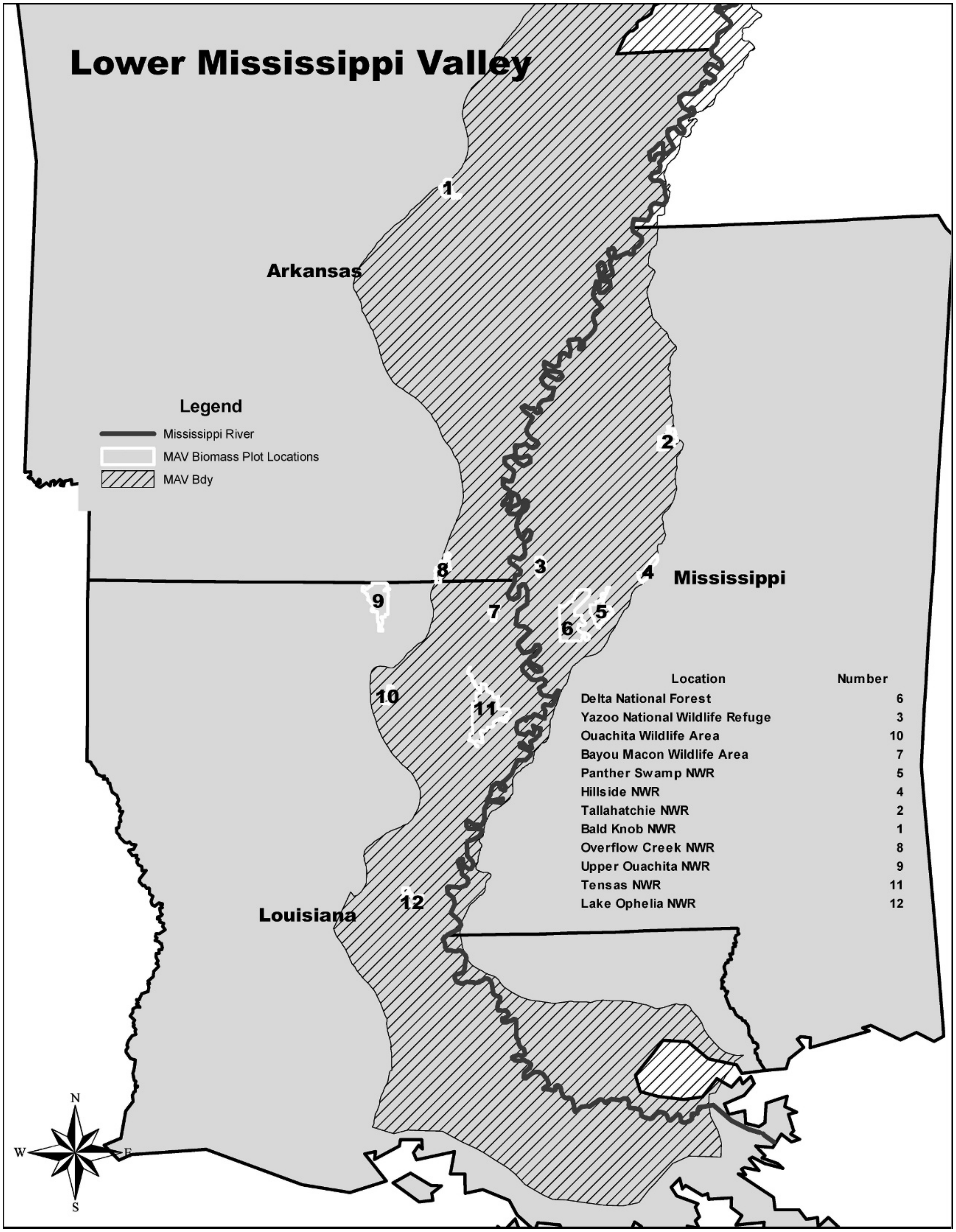

Figure 1. Location of bottomland hardwood field measurement sites in the Lower Mississippi Valley.

Table 1. Summary of even-aged bottomland hardwood plantations measured from the Lower Mississippi Valley region.

Location	Map No.	Stand Age	Sample Size (# of plots)	Year of Measurement	Planting Density (stems/ha)	Dominant Planted Species
Lake Ophelia NWR, Marksville, Louisiana	12	7	3	2007	748	bottomland oaks
Overflow NWR, Parkdale, Arkansas	8	7	2	2007	748	bottomland oaks
Tallahatchie NWR, Grenada, Mississippi	2	7	3	2007	748	bottomland oaks
Tensas River NWR, Tallulah, Louisiana	11	7	6	2007	748	bottomland oaks
Tensas River NWR, Tallulah, Louisiana	11	7	8	2007	748	bottomland oaks
Upper Ouachita NWR, Farmerville, Louisiana	9	7	3	2007	748	bottomland oaks
Upper Ouachita NWR, Farmerville, Louisiana	9	7	5	2007	748	bottomland oaks
Bald Knob NWR, Augusta, Arkansas	1	7	2	2007	748	bottomland oaks
Panther Swamp NWR, Yazoo City, Mississippi	5	8	2	2007	748	bottomland oaks
Hillside NWR, Cruger, Mississippi	4	8	3	2007	748	bottomland oaks
Panther Swamp NWR, Yazoo City, Mississippi	5	10	5	2001	748	bottomland oaks
Yazoo NWR, Hollandale, Mississippi	3	10	5	2001	748	Nuttall oak, willow oak, water oak
Bayou Macon WMA, East Carroll, Louisiana	7	15	3	2008	748	bottomland oaks and green ash
Hillside NWR, Cruger, Mississippi	4	15	10	1999	890	Nuttall oak
Hillside NWR, Cruger, Mississippi	4	15	10	1999	890	Nuttall oak
Yazoo NWR, Hollandale, Mississippi	3	17	16	1999	890	willow oak, water oak, cherrybark oak
Hillside NWR, Cruger, Mississippi	4	17	9	1999	890	willow oak, water oak, cherrybark oak
Yazoo NWR, Hollandale, Mississippi	3	17	10	1999	890	willow oak, water oak, cherrybark oak
Ouachita WMA, Monroe, Louisiana	10	21	7	2007	478	Nuttall oak
Ouachita WMA, Monroe, Louisiana	10	22	5	2007	478	Nuttall oak
Delta NF, Rolling Fork, Mississippi	6	23	6	2001	889	bottomland oaks and green ash
Delta NF, Rolling Fork, Mississippi	6	29	7	2007	889	bottomland oaks and green ash
Yazoo NWR, Hollandale, Mississippi	3	33	3	2001	1345	cherrybark oak, Nuttall oak
Yazoo NWR, Hollandale, Mississippi	3	33	2	2001	1345	cherrybark oak
Yazoo NWR, Hollandale, Mississippi	3	34	10	2007	1345	Nuttall oak
Yazoo NWR, Hollandale, Mississippi	3	34	5	2007	1345	swamp chestnut oak
Yazoo NWR, Hollandale, Mississippi	3	34	5	2007	1345	cherrybark oak, Nuttall oak

Table 1. Continued.

Location	Map No.	Stand Age	Sample Size (# of plots)	Year of Measurement	Planting Density (stems/ha)	Dominant Planted Species
Yazoo NWR, Hollandale, Mississippi	3	39	5	2007	1345	cherrybark oak, Nuttall oak
Yazoo NWR, Hollandale, Mississippi	3	39	5	2007	1345	cherrybark oak

NWR = National Wildlife Refuge, WMA = Wildlife Management Area, NF = National Forest.

equations for hardwood species groups derived by Jenkins et al. (2003) and hereafter expressed as total live tree biomass (Mg/ha). Carbon fraction of dry biomass was assumed to be 0.5 (Swift et al. 1979).

As our interest was in modeling development at the stand level, we constructed chronosequences using stand level averages. Effective sample size was 29 and 38 stands for the planted and naturally regenerated datasets, respectively, and 67 stands for the pooled datasets. We lacked sufficient data to construct chronosequences for specific soil types, species compositions, or initial planting densities, but acknowledge these as sources of variability in a generalized model representing bottomland hardwood forest development across a range of sites and practices in the LMV.

We used the Richards function (Richards 1959, Pienaar and Turnbull 1973, Seber and Wild 1989) to model stand level total live tree biomass carbon over time from the chronosequences. This sigmoidal-shaped model captures the reduced diameter growth typical of newly established stands of bottomland oaks (Kennedy 1993). The equation is:

$$f(x) = \left[\alpha^{1-\delta} - e^{-kx}\right]^{1/(1-\delta)}$$

where x is stand age in years, and $f(x)$ is total live tree biomass carbon Mg per ha at age x, with parameters α, κ, and σ. Models were fitted using SAS v.9.1 PROC NLIN (SAS Institute Inc. 2003). We calculated the 95% confidence and prediction intervals, mean squared error, residual standard deviation, coefficient of determination and P value for the modeled output.

Fitted model parameters served to compare chronosequences assembled separately for planted and naturally regenerated stands. While the parameters for regression models may not be significantly different, it is difficult to definitively conclude that they are equivalent (Kleijnen et al. 1998). Consequently, we further relied on graphical validation to justify pooling data (Huang et al. 2003), plotting data from planted and naturally regenerated stands from the same age range.

We evaluated our chronosequence-based model against the U.S. Department of Energy regional estimate for oak-gum-cypress stands with afforestation of land in the South Central U.S. (Smith et al. 2006), which is the operative estimate for bottomland hardwood afforestation in the LMV used in the U.S. Department of Energy's Voluntary Reporting of Greenhouse Gases 1605(b) Program.

RESULTS

Accrual of total live tree biomass carbon over time can be inferred from the chronosequences (Figure 2). Planted and naturally regenerated stands

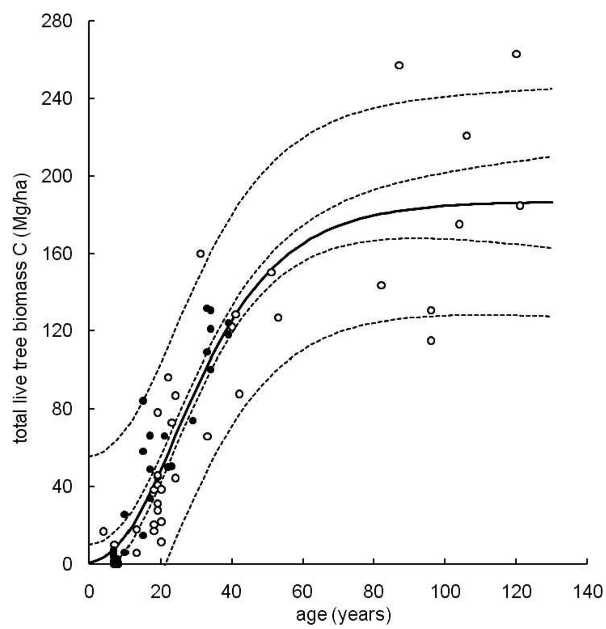

Figure 2. Chronosequence of even-aged planted (solid circles) and naturally regenerated (open circles) bottomland hardwood stands of known age in the Lower Mississippi Valley. Data points represent stand level averages of live tree above- and below-ground biomass carbon (n = 67 stands). Modeled total live tree biomass carbon (Mg/ha) = $(186.7^{(1-0.8696)} - \exp^{(-0.0577 * age)})^{(1/(1-0.08696))}$ (R^2 = 0.83, residual standard deviation = 26.87) with 95% confidence (inner dashed lines) and prediction intervals (outer dashed lines).

in the 31 to 42 year age class had comparable average total live tree biomass carbon of 119 (n = 7) and 113 Mg/ha (n = 5), respectively. Fitted Richards model parameters independently derived for plantations (ages 7–39 years) and naturally regenerated stands (ages 7–42 years) from roughly the same age range, were not significantly different ($P > 0.05$). Graphical validation reinforced the suggestion that the trajectory was similar for this time period (Figure 2). On the basis of this result, we pooled the data to produce a chronosequence of combined planted and naturally regenerated bottomland hardwood stands of known age from the LMV, and assume that plantations will continue to follow the trajectory of natural stands.

The Richards model fitted to the resulting dataset was

$$\text{total live tree biomass carbon} = \left[186.7^{1-0.8696} - e^{-0.0577*age}\right]^{1/(1-0.08696)}$$

where total live tree biomass carbon is in Mg/ha and age is in years (residual standard deviation = 26.87, mean squared error = 721.8, $R^2 = 0.83$, $P < 0.0001$, n = 67 stands) (Figure 2). The lower bound of the 95% confidence interval of our chronosequence-based model exceeded the U.S. Department of Energy regional estimate (Smith et al. 2006) from ages 20 through 90 years (Figure 3). Following a peak difference at year 50, when our modeled live tree biomass carbon was 59% greater than the U.S. Department of Energy regional estimate, the two models trended toward convergence.

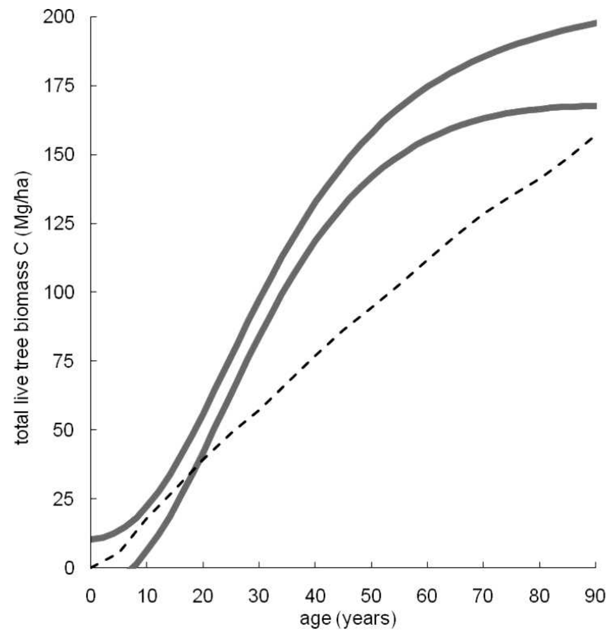

Figure 3. Comparison of live tree biomass carbon growth models for bottomland hardwoods in the Lower Mississippi Valley. Solid bounds represent 95% confidence interval of model for even-aged planted and naturally regenerated bottomland hardwood stands where total live tree biomass carbon (Mg/ha) = $(186.7^{(1-0.8696)} - \exp^{(-0.0577\ *\ age)})^{(1/(1-0.08696))}$. Dashed line represents regional estimate of live tree above- and below-ground biomass yields for oak-gum-cypress stands with afforestation of land in the South Central U.S. (Smith et al. 2006).

DISCUSSION

Our chronosequence model serves to project carbon sequestration for bottomland hardwood afforestation in the LMV and inform investment decisions driven by returns of forest carbon offsets. A better understanding of potential returns on investment will build the confidence of carbon offset markets in afforestation activities and promote an emerging source of finance for land managers engaged in wetland restoration.

At \$6 per metric ton CO_2 equivalent, as valued on the Chicago Climate Exchange on April 14 2008 (http://www.chicagoclimatex.com/ accessed April 15 2008), present value of 50 years of carbon sequestration, annually discounted at 6%, totals \$356 per acre. Expressed as a mean annual increment calculated at year 50 of 4.43 metric tons of CO_2 equivalent acre^{-1} year^{-1}, this represents nominal value generated of \$27 acre^{-1} year^{-1}. Alone, this amount is insufficient to offset current opportunity costs on private lands related to agricultural rental rates, which averaged \$72–93 acre^{-1} year^{-1} in the LMV region of Mississippi in 2007/2008 (Martin 2008). Hence to date, afforestation projects funded solely by carbon finance have mainly occurred on state and federal lands where projects do not compete with agriculture. Nevertheless, the value of carbon as a newly marketable ecosystem service can make an important contribution to overall costs of bottomland hardwood afforestation.

As a decision support tool, it is important that the modeled estimate be applied and expressed at the same scale as it was derived, namely as the predicted total live tree biomass carbon for the average bottomland hardwood stand from across a range of conditions (soil type, species composition, planting density) and from throughout the LMV region. Predicting outcomes on specific stands should instead use the prediction interval derived here or a growth and yield model like the FVS southeastern variant (FVS-SE) for stand level projections where input inventory data are available. FVS-SE has recently been validated for bottomland hardwood growth in the Yazoo-Mississippi river floodplain region of Mississippi and the Delta National Forest against stand reconstruction (Hohl et al. unpublished) and chronosequence data (Hohl 2007), respectively.

The corresponding U.S. Department of Energy look-up table (Smith et al. 2006) for the South Central U.S. region underestimates carbon storage in live tree biomass of bottomland hardwood stands in the LMV aged 20 through 90 years. While some of this difference, particularly in the intermediate stages of stand development, results from the linear shape of the U.S. Department of Energy model, there are also important differences in the data from which that model was derived. The U.S. Department of Energy estimates were modeled from data collected through the U.S. Forest Service Forest Inventory and Analysis program and necessarily include data from degraded and under-stocked stands, or stands subjected to severe natural disturbance, that are not represented in our more selective dataset.

Differences between our model and the U.S. Department of Energy regional look-up table may also be explained in part by geographical differences in forest productivity. The LMV constitutes a distinct ecoregion (Bailey 1983) and it is not surprising that forest productivity differs from broader regional averages. The South Central U.S. region as defined by Smith et al. (2006) includes not only portions of Arkansas, Louisiana, Mississippi, Tennessee, and Kentucky outside the LMV, but also the entire states of Alabama, Oklahoma, and Texas. Thus, the model developed here does not supplant the DOE regional estimate, but rather provides a more accurate projection for a subset of this region.

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